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The Effects of a Selected Wheel Design and Caster Fixture Design on Pushing Force When Pushing Four Wheeled Industrial Carts

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THE EFFECTS OF A SELECTED WHEEL DESIGN AND CASTER FIXTURE DESIGN ON PUSHING FORCE WHEN PUSHING FOUR WHEELED INDUSTRIAL CARTS

by

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ABSTRACT
THE AFFECTS OF A SELECTED WHEEL DESIGN AND CASTER FIXTURE DESIGNS ON PUSHING FORCE WHEN PUSHING FOUR WHEELED INDUSTRIAL CARTS

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Under the Supervision of Dr. Wilkistar Otieno

Manual material handlings tasks, many of which require pushing and pulling are common in almost all industrial and service sector environments. These tasks expose workers to musculoskeletal stresses as well as other related slipping and tripping hazards. The company sponsor of this study sought to lower the risk of injury from manually pushing and pulling carts. The company wanted to evaluate a newer style of split wheel and also an offset pivot dual orbital caster, which the manufacturer states will reduce pushing and pulling force. A total of eight participants (4 male, 4 female) were included in the study. Participants were required to push a four-wheeled cart 16 times for 10 meters. The cart was pushed 8 times with a total gross weight of 250 lbs (113.4 kgs) and another 8 times with 750 lbs (340.2 kgs). Only the rear wheels could swivel and were tested both perpendicular and inline to the direction of travel. The split wheel was compared to a single wheel and the dual orbital caster was compared to a standard style of caster.

All possible combinations were tested. Applied force was measured and analysis was conducted on instantaneous peak force.

Results showed that the caster design did not significantly affect the initial applied force. However, the dual orbital caster was consistent in the amount of applied force when the wheels were perpendicular or aligned to the direction of travel. The dual orbital caster resulted in lower initial applied forces when used together with the single wheel design. In addition, the dual orbital caster showed marked decrease in the applied push force when wheels where positioned perpendicular to the direction of travel compared to the standard caster. These results strengthen the recommendation for the company to invest in the dual orbital – also referred to offset pivot caster. Secondly, though the wheel type significantly affected the applied force the mean applied force difference between the two wheel types was not practically significant enough to warrant a change of the wheel type in the company.

This thesis is dedicated to my wonderful wife who encouraged me throughout the entire program. It is also dedicated to my children as a reminder of the necessity to persevere to the end.

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Chapter 1: Research Background

Manual material handling tasks can be found in many industrial and service sector environments. Much focus and attention in research has been given to reducing risk factors associated with lifting and lowering of parts, components, or boxes in the workplace. The National Institute of Occupational Safety and Health (NIOSH) first published their Lifting Guide in 1981 [2]. Since that time, industry has responded by working to reduce the amount of manual lifting, lowering, and carrying found in workplaces, often replacing those tasks with pushing and pulling [3]. In certain industries, pushing and pulling maneuvers can account for an estimated 50% of the manual material tasks [1].

In the workplace, overexertion from an outside source was ranked as the highest cause of disabling injuries. These injuries included those involving pushing, pulling, lifting, or throwing. In 2011, injuries related to material handling cost business $14.2 billion in direct expenses [4].

It is estimated that 9-20% of lower back injuries in the industrial environment are associated with pushing or pulling tasks [5]. In the state of Ohio, the total annual cost for back injuries is over $100 million dollars while the average cost of a back injury is $18,290 per occurrence [6]. According to the state of Texas Department of Insurance, the average cost for a back injury is $15,000. Back injuries also account for 24% of the worker's compensation injuries in Texas [7]. In addition to increasing risk of injury to the back, pushing and pulling has led to increased discomfort in the shoulders of workers who manually push carts on a regular basis [8]. According to NIOSH, approximately 600,000 employees are afflicted with back injuries annually, at a cost of over $50 billion [26]. An undocumented but believed to be significant portion of these injuries and costs are attributable to pushing and pulling tasks.

The sponsor of this study, a manufacturer of medium and heavy military trucks, tactical wheeled vehicles, and commercial vehicles has been working to reduce forces of manual pushing and pulling of carts. The company seeks to lower injuries by reducing pushing and pulling force, a presumed risk factor for injury [1]. In an effort to reduce pushing and pulling forces, they have started purchasing split wheeled casters manufactured by Aubin Industries of Tracy, California. In addition to the split wheel caster named Swivel-Eaz™, Aubin Industries and has developed a new style of caster fixture called a Swivel-Eaz™ Pro. The sponsor of the study seeks to verify the manufacturer's claims that both products reduce the force required to push or pull a cart.

This research study was designed to respond to the sponsoring company's concerns. We seek to determine if the split wheel and offset pivot caster individually or interactively have an effect on either initial or sustained force when compared to a standard single wheel and caster design. To realize this goal, we sought to test the following three hypotheses, which will be discussed in detail in Chapter 3 of this thesis.

1. Split-wheel design will affect the initial applied peak force required to move a four wheeled cart

2. The offset pivot caster mounting will affect the initial peak applied force required to move a four wheeled cart.

3. There is a statistically significant interaction between wheel type and caster type on the initial applied peak force required to move a four wheeled cart.

Chapter 2: Literature Review

2.1 Force/Load Guidelines

In the United States, the Occupational Safety and Health Administration (OSHA) has neither established a safe threshold on the weight of a cart and its contents, nor the maximum force an individual is allowed to push or pull. The often-used guideline in general industry for pushing and pulling comes from the psychophysical research that was conducted at the Liberty Mutual Research Center by Snook and Ciriello in 1991 [9]. To use the tables developed by Snook and Ciriello, the user must identify the following: task (pushing or pulling), gender, height of the hands while pushing or pulling, frequency of the task, and the distance traveled. The goal is to design the task so it can be safely accomplished by 75% and 99% of the female and male workers, respectively [9].

2.2 Related Prior Research

Table 1 is a chronological summary of published research directly or indirectly related to this study.

Table 1 - Related Research

Related	Article Title	Author	Year	Movement/job	Method of data collection Experiments/ -Variables	Methodology -Type of analysis -Statistics (Qualitative v Quantitative)	Remarks (findings)
Direct	Effect of handle height on lower back loading in cart pushing and pulling	Lee, Chaffin, Herrin, Waikar	1991	Pushing/pulling study, biomechanical	6 subjects	Force Measurements, ANOVA force and biomechanical loading	Pushing results in lower compressive force than pulling
Direct	Kinematics, kinetics, psychophysical perceptions in symmetric and twisting pushing and pulling tasks	Resnick, Chaffin	1996	Pushing study	10 males	Force Correlations	Psychophysical ratings were significantly correlated with peak push and pull hand forces but not peak velocity.
Direct	Pushing and pulling in relation to musculoskeletal disorders: a review of risk factors	Hoozeman et al	1998	Biomechanical	Literature review	Epidemiological	Risk factors for pushing and pulling include work situation, distance, frequency, handle height, cart weight. Actual working method, posture/movement/exerted force, foot distance and velocity. Worker characteristics such as body weight.
Direct	Factors affecting minumum push and pull forces of manual carts	Al-Eisawi et al	1999	Push/pull forces of manual cart	Used a wagner push/pull force gauge to measure force. Variables: Wheel width, floor material, wheel diameter, wheel orientation, push v pull,	Least squares regression analysis, quantitative	Wheel width: no significant effect Wheel orientation: generally affected the force Push v Pull: no difference

Related	Article Title	Author	Year	Movement/job	Method of data collection Experiments/ -Variables	Methodology -Type of analysis -Statistics (Qualitative v Quantitative)	Remarks (findings)
Direct	The effect of handle height and cart load on the intial hand forces in cart pushing and pulling	Al-Eisawi et al	1999	Pushing/pulling and hand force	5 males, 5 females	ANOVA	Very similar to my methods of data collection, For heavier carts, lower forces are applied at heigher handle heights
Direct	Integrating Human Factors and Engineering Concepts into Trolley Design	Wilkinson	2000	Push/pull forces of manual cart	Interview, and push force measurement. Details into methodology are slim. Castor design (angle), floor surface, handle design	Interview, and push force measurement. Details into methodology are slim qualitative and quantitative	Wheel profile: flat profile turned easier on carpet than round Floor surface: had an effect Handle design: contributes to difficulty Castor angles determine the turn around performance of the caster.
Direct	Force direction and physcial load in dynamic pushing and pulling	Looze, grueningen et al	2000	Pushing study	8 male	ANOVA, force comparisons	Handle height affects the direction of force exertion, which influences he shoulder and low back load.
Direct	Mechanical load on the low back and shoulders during pushing and pulling of two-wheeled waste containers compared with lifting and carrying of bags and bins	Schibye, Sogaard, Martinsen, and Klausen	2001	Pushing/pulling study	7 males	Biomechanical load	Torques at the low back and shoulders are lower during pushing and pulling compared to lifting of the same amount of waste.
Direct	Evaluation of ergonomic adjustments of catering carts to reduce external pushing forces	Jansen, Hoozemans, Beek, Frings-Dresen	2002	Push force study	4 female	ANOVA and interactions	Good example of resultant force, determining initial, and sustained

Related	Article Title	Author	Year	Movement/job	Method of data collection Experiments/ -Variables	Methodology -Type of analysis -Statistics (Qualitative v Quantitative)	Remarks (findings)
Direct	Ergonomics evaluation and redesign of a hospital meal cart	Das, Wimpee, Das	2002	Push force study	11 males and 13 females	Mann-whitney test	Recommendations on hospital meal cart criteria
Direct	Mechanical loading of the low back and shoulders during pushing and pulling activities	Hoozeman et al	2004	Pushing/pulling study, biomechanical	7 subjects	Biomechanical,	Intitial exerted forces were found to be the higheset exerted forces during the pushing and pulling activities.
Direct	The dynamics of pushing and pulling in the workplace	Tony Brace	2005	Literature review	Literature review	Literature Review	Recommendations on design criteria and load for pushing and pulling.
Direct	Pushing and pulling carts and two-wheeled hand trucks.	Jung, Haight, Freivalds	2005	Literature review		Literature review to determine recommendations	Recommendations on handle height, caster diameter, COF, ramp grade
Direct	Pushing and pulling: personal mechanics influence spine load	Lett, McGill	2006	Pushing study	9 males	EMG Biomechanical	Technique expertise assists in assists in reducing back loads during pushing and pulling, and that some previously suggested psychophysical guidelines are in agreement with biomechanical load guidelines
Direct	The evaluation of force exertions and muscle activities when operating a manual guided vehicle	Lin, Chen, Wei, Wang	2009	Pushing force and muscle EMG	5 male, 5 female	Nested-factorial design, ANOVA	F-initial in pushing/pulling a MGV was the greatest. Two first front wheels and two rotatable wheels, the F-initial and F-Ending responses with 15.3 diameter were significantly lower than thos for a cart with 20.3 cm diameter wheels.

Related	Article Title	Author	Year	Movement/job	Method of data collection Experiments/ -Variables	Methodology -Type of analysis -Statistics (Qualitative v Quantitative)	Remarks (findings)
Direct	Description and analysis of hand forces in medicine cart pushing tasks	Boyer, Lin, Chang	2012	Pushing/pulling and hand force	22 subjects	Normality, collinearity, paired t tests,	Floor surface, lane congestion, and precision control are associated with horizontal hand force across cart pushing motion phases.
Direct	Psychophysical basis for maximum pushing and pulling forces: A review and recommendations	Garg, Waters, Kapellusch, Karwowski	2014			Literature Review	Complete Lit review of several factors in pushing pulling tasks. -Pushing v pulling: inconsistant results in strength -Wheels: harder wheels roll easier -Swiveling of wheels affect force -Floor surface, weight, affect force -Handle height: inconsistent
Indirect	A study of size, distance, height, and frequency effects on manual handling tasks	Ciriello and Snook	1983	Biomechanical	10 males and 12 female industrial workers	Psychophysical methods	Results indicate that maximum acceptable weights and forces for female workers are significantly lower, but propotionally similar, to maximum acceptable weights and forces for male workers
Indirect	Risk indicators in low back pain	Pope	1989	Epidemiological, psychosocial	Literature review	Literature Review	Provides percentages of injuries related to pushing or pulling

Related	Article Title	Author	Year	Movement/job	Method of data collection Experiments/ -Variables	Methodology -Type of analysis -Statistics (Qualitative v Quantitative)	Remarks (findings)
Indirect	The design of manual handling tasks: revised tables of maximum acceptable weights and forces	Snook and Ciriello	1991		4 new manual handling experiments are reviewed	Psychophysical methods	Revised tables were presented
Indirect	Effect of push handle height on net moments and forces on the musculoskeletal system during standardized wheelchair pushing tasks	Van Der Woude, Koningsbruggen, Kroes, Kingma	1995	Pushing biomechanical study	8 females	ANOVA , Tukey, Pearson	Biomechanical loading when pushing a wheelchair is partly influenced by push handle height.
Indirect	Distributions of manual materials handling task parameters	Ciriello et al	1999	Epidemiological	Study of 25,291 manual material handling tasks from 2442 reports	Epidemiological	Presented examples of parameters to improve ergonomic design i.e... decreasing distance of pushes, pulls, and carries
Indirect	Survey of manual handling tasks	Ciriello and Snook	1999	Epidemiological	13 year study of 2442 industrial locations in the US.	Epidemiological	A sample of lifting and lowering tasks from industry exceed guidelines set forth by NIOSH
Indirect	Maximum acceptable horizontal and vertical forces of dynamic pushing on high and low coefficient of friction floor	Ciriello, McGorry, and Martin	2001	Pushing study	8 male	MAWs	MAWs were lower on a low COF than on a higher COF

Related	Article Title	Author	Year	Movement/job	Method of data collection Experiments/ -Variables	Methodology -Type of analysis -Statistics (Qualitative v Quantitative)	Remarks (findings)
Indirect	Definition and assessment of specific occupational demands concerning lifting, pushing, and pulling based on a systematic literature search	Bos et al	2002	Literature Search	Literature search	Literature Review	More attention should be paid to: 1. the definition of demands, 2. assessment of specific demands, 3. quality of tests for specific occ demands.
Indirect	Low-back and shoulder complaints among workers with pushing and pulling tasks	Hoozeman, Beek, Frings, et al	2002	Literature review	459 workers	Epidemiological	Strong relationship between pushing and pulling and shoulder complaints
Indirect	Pushing and pulling in association with low back and shoulder complaints	Hoozeman, Beek, Fings, Woude, and Dijk	2002	Literature review	434	Epidemiological	Strong relationship between pushing and pulling and shoulder complaints
Indirect	Low-back biomechanics and static stability during isometric pushing	Granata, Bennet	2005	Pushing study	11 participants	Biomechanical	If one maintains stability by means of cocontraction, additional spinal load is created, increasing risk of overload injury
Indirect	Interface stability influences torso muscle recruitment and spinal load during pushing tasks	Lee, Granata	2006	Biomechanical	14 subjects	ANOVA of EMG	Handle or interface stability may influence spinal load and associated risk of musculoskeletal injury during MMH tasks that include pushing exertions.
Indirect	Biomechanical and physiological analysis of a luggage-pulling task	Jung, Haight, Hallbeck	2007	Biomechanical	4 males	ANOVA, wheel diameter and biomechanical force	Large wheels are prior to handle height, pole angle and handle rotation for an ergonomic luggage design.

Related	Article Title	Author	Year	Movement/job	Method of data collection Experiments/ -Variables	Methodology -Type of analysis -Statistics (Qualitative v Quantitative)	Remarks (findings)
Indirect	Dynamic pushing on three frictional surfaces: maximum acceptable forces, cardiopulmonary and calf muscle metabolic reponses in health men	Maikala, Dempsey, Ciriello, O'Brien	2009	Pushing/pulling study	12 males	Psychophysical O2 uptake, cardiopulmonary, peripheral metabolic data	Results from high inertia cart suggest the importance of considering the influence of frictional surface on dynamic pushing to better approximate real world scenarios. Study used ANOVA for statistical analysis
Indirect	Effects of handle orientation, gloves, handle friction and elbow posture on maximum horizontal pull and push forces	Seo, Armstrong, Young	2010	Biomechanical modeling	4 male, 4 female	ANOVA	Push/pull tasks contribute to 20% of all industrial back injuries in the united states

This study is different from others that have previously been conducted as it compares the newer split wheel design to a standard single wheel which is commonly used in many industries. Additionally, the Swivel-Eaz ™ Pro swivel caster was recently patented and is new to the market; therefore it has not been studied in the past.

This study will contribute to the body of knowledge by filling in the dearth of research that specifically studies the effect of Swivel Eaz™ wheels and Swivel Eaz™ Pro casters in the push and pull forces.

2.3 Factors Affecting Pull and Push Forces

In the industrial setting, employees may be required to push carts with various loads. There are several different factors that contribute to the actual force required to move the cart including: friction, wheel position, wheel diameter, wheel hardness, floor slope, and the cart and content weight. *Initial* force is defined as the force required to get an object in motion while *sustained* force is the force required to keep an object in motion [9]. All data analysis in this study was conducted on the peak instantaneous applied force recorded during the initial phase while the cart was being pushed. For convenience in identification, the peak instantaneous force is the highest point found in a tenth of a second in time during the initial pushing phase. Herein after, the peak instantaneous force is referred to as peak applied force or peak force.

Weight

In a vehicle assembly plant, workers may be required to push carts that are full of metal parts which are relatively heavy; or they could push a small cart of lightweight plastic components. At times, workers may be required to push or pull loads of various weights including those which may require near maximal strength to move. For instance, Ciriello et al. (1999) analyzed 25,291 manual material handling tasks of which 1,879 required pushing and 1,866 required pulling. They found that 28 % of the pushing tasks required forces greater than 70 lbs (311 N) [15]. In yet another study, Resnick (1996) found that the mean static peak horizontal force was 75 lbs (335 N) for women and 139 lbs (620 N) for men. These peak forces were found with a handle height of about 80 % of shoulder height [16]. Load weights that are transported in most industries can vary up to 3,300 lbs (1,500 kgs) which far exceed the recommend weight limit of 496 lbs (225 kgs) for four wheeled carts and 251 lbs (114 kgs) for two wheeled carts [13]-[14]. In this study, two different load weights were used 250 lbs (113 kgs) and 750 lbs (340 kgs).

Friction/Wheel Hardness

Friction is defined as a "force that acts to resist the relative motion (or attempted motion) of objects or materials that are in contact" [27]. In wheeled carts, friction between the wheel and the axle and rolling resistance between the floor and the wheel determine the amount of force required to move the cart [1]. Higher friction contributes to increased rolling resistance and thus relatively higher pushing and pulling forces. For this reason, low-friction wheel bearings, and relatively hard wheels are preferred when pushing and pulling carts with heavier loads [10]-[13].

The relationship between the rolling resistance, friction, and load is governed by the following equation [28]-[29]:

$F = f \times W/R$

F = the force required to overcome the rolling friction

f = the coefficient of rolling friction (units must match same units as R (radius))

W = Load on the wheel

R = Radius of the wheel

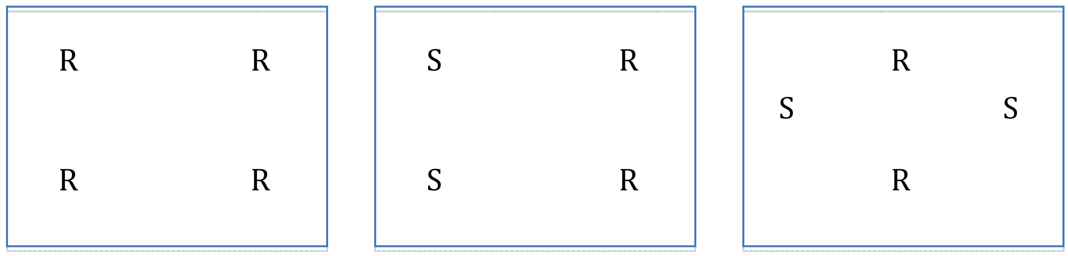
It takes less force to push or pull hard wheels than soft wheels due to a lower rolling friction [10]. Soft wheels or pneumatic wheels tend to develop flat spots when a cart loaded with a heavy weight is stored for a long period of time [13].

Wheel Position/Orientation

Whether in the manufacturing or the service sector environment, it is common to find a cart with four casters having one positioned on each corner. There are other caster configurations that can be used when designing a cart, such as having a single or pair of fixed casters in the center and a swivel caster on each of the four corners which allows the cart to be positioned and maneuvered into tight spaces [12]. Some carts have two fixed casters and two swivels, while others have four swivels. Three more commonly found wheel positions are listed in (Figure 1) where "R" represents a ridged or fixed caster and "S" is a swivel caster. Wheels in the study were positioned as depicted in Figure 1b.

Figure 1 - Wheel Positions

(1a) (1b) (1c)



Is this study, two swivel casters were mounted on one end of the cart nearest the handle and two fixed casters were mounted on the opposite end.

The manufacturer Darcor Casters and Wheels, defines *Swivel Caster* as a basic caster unit with the addition of a bearing that allows the caster to swivel about a vertical axis [30]. One of the problems with having a set of swivel wheels on a cart is occasionally the wheels are not aligned in the direction of travel. When this happens, additional force is required to get the cart wheels to swivel around and become properly aligned in the direction of travel. According to a study by Al-Eisawi et al., when front wheels of a cart were aligned in the direction of travel and rear wheels were perpendicular to the direction of travel, minimum pull force was 19% higher than the minimum push force. This suggests that swivel wheels should be placed in the rear if the cart will be primarily pushed [10].

Swivel wheels affect the amount of force required when pushing or stopping a cart [10]. Al-Eisawi et al. also found that when the rear two swivel casters are aligned perpendicular to the direction of travel the average force was 13.1% higher than when all four casters were aligned in the direction of travel. In addition, they found that when all four swivel casters were aligned perpendicular to the direction of travel the average force was 30.7% higher than when all four were aligned to the direction of travel. As a result of their study, they found that the smallest force required to move the cart was recorded when all four wheels were aligned in the direction of travel. Additionally, the greatest force was recorded when all four wheels were aligned perpendicular to the direction of travel [10]. Therefore, in this study the front wheels were fixed to the direction of travel, while the rear wheels were positioned both in-line and perpendicular to the direction of travel as will be reported in the design of experiment.

A four-wheeled cart needs to have at least two wheels that swivel to allow it to turn. Carts with four swivel wheels require more force to operate [10]. The extra force required to operate a four-wheeled cart with swivel wheels could be related to the additional force that is applied to keep it under control in the lateral direction [1]. In this study, lateral force was measured to determine if it decreased with any of the new caster designs or combinations.

As four-wheeled carts are commonly found in the company sponsoring this study, a four-wheeled cart was constructed with swivel wheels positioned at the rear closest to the handle.

Wheel Diameter

Generally, the effect of wheel diameter on the push and pull force is modeled using the equation described in the previous section entitled Friction; where R = radius, W = load on the wheel, f = coefficient of rolling friction, an F = force required to overcome rolling friction.

$$F = f \times W/R$$

Therefore if all other factors are equal, by doubling radius of the wheel, push and pull force will decrease by half. Increasing the diameter of a wheel can be an effective measure in reducing the force needed to move a cart. In a study of pushing floor-based patient lifting devices, it was found that there were higher sheer forces in the user's back when pushing the device with smaller diameter wheels compared to a similar lifting device equipped with larger diameter wheels [1]. Irrespective of the floor surface (carpet or concrete), pull force decreased when wheel diameter was increased [10]. However, push and pull force is greater with larger wheels when swivel wheels are not aligned in the direction of travel [10]. Larger diameter wheels are able to cross over bumps, holes, and other obstructions in the floor more effectively than smaller wheels [1]. In this study, diameters of the wheels chosen were 6 in. (15.2 cm) because this dimension is primarily used in the sponsoring company. In addition, with this diameter, any bumps in the concrete in the testing facility would not interfere with the data collection protocol.

Slope

In some general tasks such as moving products using two-wheeled handcarts, stairs and curbs can create an obstacle that is difficult for the cart to get over. An option may be to install a ramp to help navigate the steps or curb; although an increase in slope will cause an increase in push and pull force. It is recommended that when using a ramp the slope should be kept to less than 3.5% (2°) [15].

Handle Height

Al-Eisawi et. al (1999) reported no statistical difference in push force with a load weight of 160 lbs (73 kgs) at three different handle heights; knuckle, elbow, shoulder. However, the difference was significant at a load weight of 399 lbs (181 kgs). Push force required when handle height was at the shoulder level was 10% lower than at elbow height, and elbow height was 10% lower than knuckle height [11]. The preferred handle height for horizontal pushing is at about elbow height [13]. In addition, biomechanical research has found compression force on the L5/S1 vertebrae was lowest when handle height is set at elbow height [16].

Handle Width

Handle width should be designed no greater than 18 in. (45.7 cm). Wider handles may place higher loads on the weaker shoulder muscles [13]. In this study, the handle width was fixed at 20 in. (51 cm).

Chapter 3: Current Study

3.1 Study Variables

The following summarized variables were considered in this study: (1) load weight (2) wheel alignment (3) caster fixture design and (4) wheel type.

One caster manufacturer, Aubin Industries located in Tracy, California has designed a wheel and caster assembly which they claim “reduces turning and rolling resistance on swivel, ridged and fixed axle systems [18].” The wheel manufactured by Aubin Industries is a split wheel design where the wheels rotate independently and share a single hub assembly as shown in (Figure 2).

Figure 2 - Swivel Eaz Wheel

Swivel-EAZ® Wheel U.S. PAT. 6,880,203 CAN. PAT. 2,453,036

According to the patent for the wheels:

> The two-wheel caster offered an improvement over the single wheel in two important regards. The ability of the wheels to rotate at different rates or in opposite directions at the same time greatly enhances the ability to turn about the vertical pivot axis, making a change in overall direction of the object much smoother [20].

The caster assembly also manufactured by Aubin Industries "allows the caster to pivot easily to accommodate the direction of thrust applied to an object supported by the caster [20]."

According to the patent for the caster:

> This advantageous feature is made possible by providing a dual pivot assembly in the caster mounting that is laterally offset, whereby the caster wheels may not only pivot about a wheel pivot axis that extends through the plane of the caster wheel, but also revolve orbitally about a mounting pivot axis that is laterally offset from the wheel axis. As a result, the caster assembly easily may assume the proper orientation for any thrust applied to the caster-supported object [20].

3.2 Research Questions

This study sought to answer the following questions:

1. Does the split wheel have an effect on either initial or sustained force when compared to a standard single wheel in various caster orientations?
2. Does the offset-pivot fixture (caster) have an effect on either initial or sustained force when compared to a standard caster fixture in various wheel orientations?
3. Do these factors: wheel type (split versus single), fixture (standard versus offset), and wheel orientation (aligned versus misaligned) have an interactive effect on the push forces?

3.3 Research Hypotheses

The overarching goal of this research is to determine the efficacy of the Swivel Eaz ™ split wheel and offset pivotal Swivel Eaz ™ Pro caster in reducing push forces that occur when manually moving a cart. To realize this goal, we set up three main aims from which we defined the research hypothesis as follows:

1. Split-wheel design will affect the initial applied peak force required to move a four wheeled cart.

Hypothesis 1 a: Split wheels will reduce the initial applied peak force when the rear wheels are positioned at 90 degrees to the direction of travel.

Hypothesis 1 b: Split wheels will affect the initial applied peak force when the rear wheels are positioned at 0 degrees (aligned with the direction of travel).

2. The "offset pivot" caster mounting will affect the initial peak applied force required to move a four wheeled cart.

Hypothesis 2 a: The offset pivot caster mounting will reduce the initial applied peak force required to move the cart when the rear wheels are positioned at 90 degrees to the direction of travel.

Hypothesis 2 b: The offset pivot caster mounting affect the initial applied peak force when the rear wheels are positioned at 0 degrees (aligned with the direction of travel).

3. There is a statistically significant interaction between wheel type and caster type on the initial applied peak force required to move a four wheeled cart.

Hypothesis 3 a: There is a statistically significant interaction between wheel type and caster type on the initial applied peak force required to move a four wheeled cart when the rear wheels are positioned at 90 degrees to the direction of travel.

Hypothesis 3 b: There is a statistically significant interaction between wheel type and caster type on the initial applied peak force required to move a four wheeled cart when the rear wheels are positioned at 0 degrees (aligned with the direction of travel).

Chapter 4: Methodology and Data Analysis

4.1 Experiment Participants

In order to begin conducting the study on human subjects, approval was obtained from the University of Wisconsin-Milwaukee Institutional Review Board (IRB). Final approval to begin this study IRB# 14.316 was given on August 13, 2014 for one year. While eight participants was the target group size, the IRB allowed a total of twelve subjects to participate in the study to allow for possible participant withdrawal.

Eight professional workers (4 male, 4 female) of various ages and occupations were recruited to participate in the study. All of the subjects were employees of the heavy truck and military vehicle manufacturer that sponsored the study and accepted to join the study voluntarily. All of the subjects worked in a professional office environment.

Subjects completed the study during their normal workday; thereby receiving their standard wage. No overtime was paid to participants nor were they paid anything beyond their normal wage. Participants who successfully completed the study received a $40 credit card, which was approved by the UWM IRB committee. Before subjects were allowed to participate in the study they completed a pre-screen form (Appendix A) as was stipulated by the IRB inclusion/exclusion protocol. The pre-screen form asked the potential participant if they had any previous injuries in their back or shoulders or if they were at the time experiencing any pain or discomfort in their back or shoulders. If they answered yes to any of these questions they would be precluded from participating in the study. If the participant successfully passed the screening process they were given the UWM-IRB committee approved consent form for review and signature. The student principal investigator met with supervisors of each potential participant to obtain approval for their employees to participate in the study. Testing was conducted onsite at the sponsoring company's test and development facility.

After the subject reviewed and signed the consent form they were ready to participate in the study. A short demographic and anthropometric form was completed that included height, weight, gender and standing elbow height (Appendix B). Participants were asked to provide their overall stature. Standing elbow height was measured in the lab. These measurements were taken with their shoes on.

Subjects were asked to push the cart once for 10 meters for each of the 16 test combinations. Testing occurred over two separate sessions for a total of 8 trials each session. To minimize the effect of muscle fatigue, subjects were allowed to rest 2 minutes between trials and were given up to 5 minutes between trials if necessary. In addition, there was a longer rest/recovery period of at least 2 days between the initial 8 trials and the later 8 trials. Voltage, speed, and time were collected during each of the trials and the experiment combination runs were randomized using a random number generator available online at random.org.

The floor of the test facility is a poured concrete pad, which is representative of the floor surface found in many factories. To maximize forward force and minimize downward force, handle height was adjusted to the same height as the participant's standing elbow height.

4.2 Equipment and Instrumentation

Cart Design

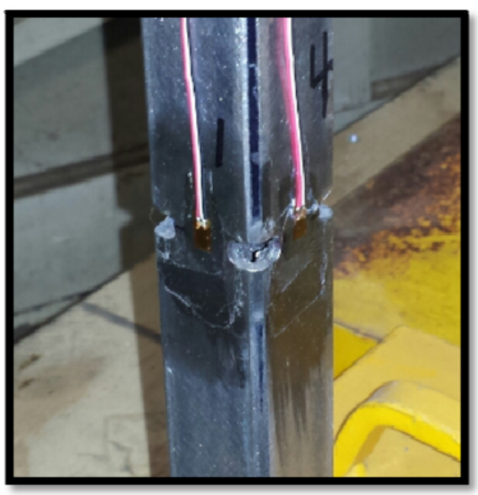
To reduce setup time between trials, two carts (herein named cart 1 and 2) were built to the same dimensions using the same construction materials found in Figure 3.

Figure 3 - Cart design

The carts were built using 1 in. (2.5 cm) rectangular steel stock which were welded together at the joints. The total dimensions of the cart platform measure 24 in. (61 cm) x 36 in. (91 cm). A 24 in. (61 cm) x 36 in. (91 cm) x ¾ in. (2 cm) thick sheet of plywood was screwed to the top of the platform frame to provide a solid surface for the weights. To allow for a quicker setup time between trials, the standard caster fixtures were installed on one cart and the Swivel Eaz ™ Pro caster fixtures were installed on the second cart. Therefore, to reduce setup time between trials, either the weight or the wheels had to be changed, never the entire fixture.

The handle was built using ¾ in. (2 cm) round steel cut and welded to the ¾ in. (2 cm) square steel stock. Overall dimension of the handle is 20 in. (51 cm). The vertical support for the handle was built using a ¾ in. (2 cm) x ¾ (2 cm) steel square tube that measures 40 in. (102 cm) in length. The vertical support was inserted into a 1 in. (2.5 cm) x 1 (2.5 cm) square tube which measured 14 in. (35.6 cm) in total length. Holes were drilled through the 1 in. (2.5 cm) x 1 in. (2.5 cm) square tube every 1 in. (2.5 cm) and a pin was inserted to support the vertical handle structure. This allowed the handle to adjust vertically to match standing elbow height of each participant. The handle was designed to be easily removed and was shared between the two carts. The vertical support for the handle was notched on all 4 edges to allow support to flex and activate the strain gauges as shown in Figure 4.

Figure 4 - Handle Notches



Weights were used to bring the total weight of the cart up to 250 lbs (113.4 kgs) or 750 lbs (340.1 kgs) depending on the trial. Weight of the carts varied due to the variability in weight of the different wheels and fixtures. Therefore, it was necessary to incorporate additional smaller weights to the cart to bring the total weight (cart and load) up to the target.

While cart load weight varies in the sponsoring company manufacturing environment, these two weight levels were selected as they are representative of the load weight range that could exist in a heavy-vehicle manufacturing environment. Preliminary force testing was completed using a handheld force measurement device (ergoFET 300 manufactured by Hoggan Health). To establish the maximum push force that the participants in this study could experience, a preliminary test was conducted in the worst-case scenario with wheels aligned perpendicular to the direction of travel and the cart was pushed to a high velocity. This initial test resulted in forces that did not exceed 50 lbs. (222N), which was well below the mean static force for both women and men reported by Resnick, (1996) [16].

Handle

The handle was designed to be adjustable, hence to be raised or lowered to accommodate the standing elbow height for each subject. To accommodate 98% of the working population [24] the handle was designed so that it could be lowered to 37 in (94 cm) and raised to 48 in (122 cm).

Caster Fixtures

All of the caster fixtures were manufactured by Aubin Industries. The dual offset swivel fixture named the Swivel Eaz™ Pro and has two separate pivot or swivel points, that allows multiple orientations (Figure 5). The Swivel Eaz™ Pro caster was compared to a standard swivel caster that is typical of what is currently being used by the study sponsor (Figure 6)

Figure 5 - Swivel Eaz Pro

Figure 6 - Standard Swivel Caster (Fixture)

Wheels

Wheels were provided by two different manufacturers. Both the single wheel and split wheel are 6 in. (15.2 cm) in diameter and were selected to ensure similar hardness. The bearings in both types of wheels were precision ball bearings of similar design. The 6 in. (15.2 cm) diameter split wheel was manufactured by Aubin Industries in Tracy, California. Per the manufacturer, the polyurethane Swivel-Eaz wheel has a hardness durometer of 70A [18]. The Swivel-Eaz wheel measures a total of 2 in. (5.1 cm) wide across both edges and has a crowned surface as shown in Figure 7.

Figure 7 - Swivel Eaz Caster

The standard style single wheel which also measures 2 in. (5.1 cm) wide and 6 in. (15.2 cm) in diameter is manufactured by Arbco Incorporated (Figure 8). It is a phenolic wheel and has a similar hardness as the Swivel-Eaz split wheel.

Figure 8 - Single Wheel

Cart Load

Steel weights were used to bring the gross weight of the cart up to 250 lbs (113.4 kgs) or 750 lbs (340.2 kgs) depending on the trial. The weight of the carts varied due to the variability in weight of the different wheels and fixtures. Therefore, each of the 4 unique caster/wheel combinations required different amounts of additional weight to achieve the gross weights of 250 lbs (113.4 kgs) and 750 lbs (340.2 kgs). A chart was created listing the possible caster/wheel combinations, their gross weight, and additional weight needed to achieve the target weight (Table 2).

Table 2 - Additional Weight Added

Combo #	Cart	Weight (lbs)	Fixture	Wheel Type	Cart & Caster Weight lbs.	396 lb Qty	50 lb Qty	20 lb Qty	Total Weight	Target	Additional Weight Needed
1	1	250	Standard	Single	118	0	2	1	238	250	-12
2	1	250	Standard	Single	118	0	2	1	238	250	-12
3	1	250	Standard	Swivel Eaz (dual)	125	0	2	1	245	250	-5
4	1	250	Standard	Swivel Eaz (dual)	125	0	2	1	245	250	-5
5	2	250	Off Set Pivot	Single	127.5	0	2	1	247.5	250	-2.5
6	2	250	Off Set Pivot	Single	127.5	0	2	1	247.5	250	-2.5
7	2	250	Off Set Pivot	Swivel Eaz (dual)	131	0	2	1	251	250	1
8	2	250	Off Set Pivot	Swivel Eaz (dual)	131	0	2	1	251	250	1
9	1	750	Standard	Single	118	1	4	1	734	750	-16
10	1	750	Standard	Single	118	1	4	1	734	750	-16
11	1	750	Standard	Swivel Eaz (dual)	125	1	4	1	741	750	-9
12	1	750	Standard	Swivel Eaz (dual)	125	1	4	1	741	750	-9
13	2	750	Off Set Pivot	Single	127.5	1	4	1	743.5	750	-6.5
14	2	750	Off Set Pivot	Single	127.5	1	4	1	743.5	750	-6.5
15	2	750	Off Set Pivot	Swivel Eaz (dual)	131	1	4	1	747	750	-3
16	2	750	Off Set Pivot	Swivel Eaz (dual)	131	1	4	1	747	750	-3

Floor

The floor of the test facility was a level poured concrete pad, which is representative of the floor surface found in many factories.

Data Collection Electronics

The handle support was notched at all four edges at 18 in. (45.7 cm) from the bottom. Strain gauges were mounted on all four sides of the handle to allow for measuring force in three axis: (X) laterally, (Y) longitudinally, (Z) and vertically. The four strain gauges were mounted to the vertical handle with tape and used to measure deflection of the handle under load. The four strain gauges were wired to a 5-channel bridge completion module. The bridge completion module was connected to the Vbox3 and was setup to run at a sampling rate of 10Hz. Data was saved on a compact flash memory card. A photo sensor was magnetically attached to the front wheel and captured speed by emitting light on the rotating wheel and counting the markers. The wheel rotation data was also recorded and later converted to speed in miles per hour. The photo sensor was also connected to the Vbox.

Calibration

To calibrate the strain gauges the cart was affixed to a bed plate. An overhead bridge crane was used to support a 500lb load cell which was attached to a ratchet device. The ratchet was used to pull against the cart in X, Y, Z orientations. The tests were conducted in 10lb increments from 0 to 100 lbs. Bending of the handle was measured and recorded. Load versus strain was recorded and used to develop a regression to allow for the data conversion. The wheel optical reader was also calibrated.

Ratings of Perceived Exertion Scale

After pushing the cart, the participant completed a perceived physical exertion questionnaire (Appendix C). Perceived exertion is a response variable and rated using the Borg CR10 scale. At the end of each trial, participants were asked to rate the level of exertion to their shoulders and back, using the Borg CR10 scale [22]. The Borg CR10 scale is a categorical psychophysical scale that provides a rating of perceived exertion (RPE). This scale has been used widely in a variety of applications such as rehabilitation and sports training to assess the intensity of a given physical procedure [23]. Additionally, they were asked to rate how well they liked or disliked the wheel and fixture combination, subject to ease of operation.

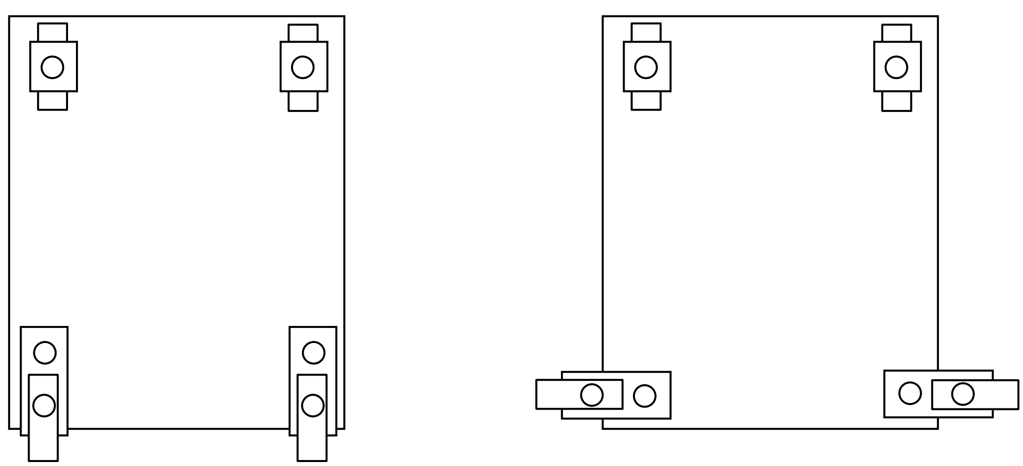
4.3 Study Design

The purpose of the research was to investigate the effects of these wheel and fixture designs on pushing force of a four-wheeled cart. We used a 2^4 balanced full factorial experiment design, with 8 participants (four male and four female). Each participant was asked to push the cart for each of the combinations (for a total of 128 experiment runs). In brief (details will be discussed in the methodology chapter), the variables that were considered include: (i) a standard commonly used 2 in. (5.1 cm) thick, 6 in. (15.2 cm) diameter single wheel versus a 2 in. (5.1 cm) thick, 6 in (15.2 cm) diameter split wheel (Swivel-Eaz ™), (ii) a standard swivel caster versus the offset-pivot orbital caster (Swivel-Eaz ™ Pro), (iii) representative load weight levels of 250 lbs (113.4 kgs) and 750 lbs (340.2 kgs), and (iv) rear wheel position (0 degree i.e. aligned to the direction of travel) versus 90 degrees (perpendicular to the direction of travel). It must be noted that all wheel, fixture, and weight combinations were tested with the front wheels fixed on 0 degrees to direction of travel. To keep the study focused on determining push force with wheels aligned in the direction of travel and also position at 90 degrees or perpendicular to the direction of travel, pushing the cart around a corner was not considered in this study.

Because the Swivel-Eaz ™ Pro has two different pivot points, the caster assembly can be oriented in multiple positions. In this study, the fixture transfer plate and wheels were positioned inline to the direction of travel (Figure 9a), herein referred to as F0R0 throughout the study. The combination was also studied with the transfer plate and wheels fully extended perpendicular to the cart (Figure 9b), herein referred to as F0R90.

Figure 9 - Wheel/Fixture Orientation

(9a) – F0R0 (9b) – F0R90



As mentioned earlier, testing occurred at sponsoring company's Test and Development facility in Oshkosh, Wisconsin. The sponsoring corporation "is a leading manufacturer and marketer of access equipment, specialty vehicles and truck bodies for the primary markets of defense, concrete placement, refuse hauling, access equipment and fire and emergency [22]."

4.4 Experimental Procedure

Subjects participated in two 60 minute sessions. A minimum of 24 hours of rest was provided between each session. At the beginning of the first session, eligible subjects completed a short demographic and anthropometric form (Appendix C) that included height, weight, gender and standing elbow height (measured in the lab with shoes on). Subjects then completed the 16 push and pull trials (Table 3) in random order, with 8 trials performed in each session.

Table 3 - Experiment Design Combinations

Combo #	Cart	Weight (lbs)	Fixture	Wheel Type	Wheel Position
1	1	250	Standard	Single	F0, R0
2	1	250	Standard	Single	F0, R90
3	1	250	Standard	Swivel Eaz (dual)	F0, R0
4	1	250	Standard	Swivel Eaz (dual)	F0, R90
5	2	250	Offset Pivot	Single	F0, R0
6	2	250	Offset Pivot	Single	F0, R90
7	2	250	Offset Pivot	Swivel Eaz (dual)	F0, R0
8	2	250	Offset Pivot	Swivel Eaz (dual)	F0, R90
9	1	750	Standard	Single	F0, R0
10	1	750	Standard	Single	F0, R90
11	1	750	Standard	Swivel Eaz (dual)	F0, R0
12	1	750	Standard	Swivel Eaz (dual)	F0, R90
13	2	750	Offset Pivot	Single	F0, R0
14	2	750	Offset Pivot	Single	F0, R90
15	2	750	Offset Pivot	Swivel Eaz (dual)	F0, R0
16	2	750	Offset Pivot	Swivel Eaz (dual)	F0, R90

To minimize the effect of muscle fatigue, subjects rested a minimum of 2 minutes between consecutive trials. Up to 5 minutes rest was provided if the subjects felt it was necessary.

Prior to each trial, the height of the cart handle was set to match the subject's standing elbow height and the cart was equipped with the appropriate wheel, caster fixture, and weight combination. The cart was moved into position and the wheels were set at either 90 degrees to the direction of travel or at 0 degrees (inline) with the direction of travel. Participants were instructed to push the cart at a steady but comfortable pace for 10 meters until they reached a predetermined stop line. The

Vbox data collection unit was set to record the force (ie, calibrated voltage), speed, and time during the trial.

After each trial the subject completed the Pain and Exertion rating form (Appendix C), and provided their subjective feedback about how well they “liked” the fixture/wheel combination. Finally, the researcher recorded the VBox trial number on the Pain and Exertion rating form and returned the cart to the start line.

4.5 Statistical Analysis

Applied peak force data was processed in Microsoft Excel 2007. Handle bending data was converted to pounds of force in lateral and longitudinal directions. Force was also recorded in the vertical direction; however due to a limitation in the design of the cart handle the strain gauge was not able to record vertical tension accurately. Therefore, only 2 axis of data were used, lateral (side to side), and longitudinal (front to back).

Since a 2^4 fully randomized factorial design was used, the peak force measurements were analyzed with a generalized linear model using a backwards elimination using Minitab version 17. Minitab performs a stepwise regression with backward elimination by starting with all predictors in the model and removes the least significant variable for each step and eventually stops when the p-value is less than or equal to the specified “Alpha-to-Remove value” [31].

Psychophysical self reported exertion data was analyzed using a Pearson's Correlation coefficient. Analysis was conducted to understand relationship between the variables and perceived exertion on the shoulder and back.

Chapter 5: Results and Discussions

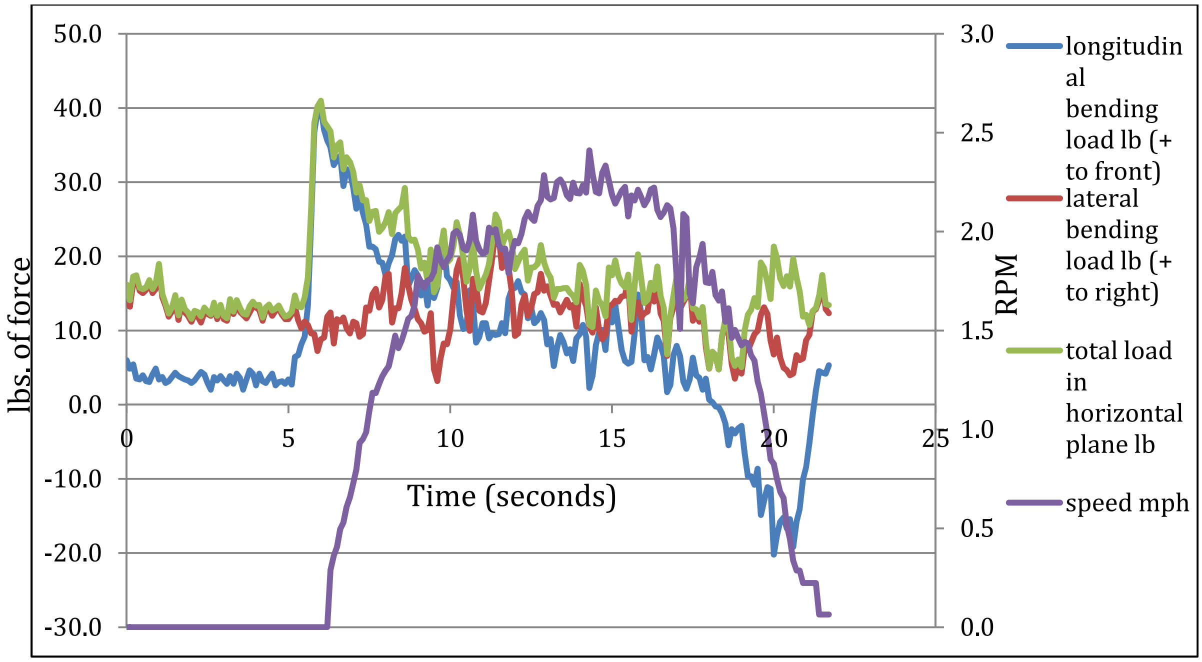
5.1 Results

Data Processing

Sampling data was collected for each trial run and saved in its raw format. Data was collected from each of the 4 strain gauges, pulse data for the wheel rotation, and time. Next, voltage from the strain gauges was converted into longitudinal and lateral bending load in pounds of force. Root mean square (RMS) value was calculated using the lateral and longitudinal bending load. Vertical load was recorded and discarded and was not used in the calculation. The design of the handle and placement of the strain gauges did not have enough sensitivity to accurately capture vertical load in the downward or upward motion. In this study, vertical load was minimized as handle height was adjusted to standing elbow height for each participant.

Pulse data from the wheel was converted to revolution per minute then ultimately converted to miles per hour. Once all of the data was converted into the required format and units of measure, data was plotted in Microsoft Excel on a scatter plot with straight lines as shown in Figure 10. Evident in Figure 10, force values became negative when the handle was bending back towards the participant to decelerate the cart (longitudinal bending).

Figure 10 - Example of Graph of Push Force



Analysis of Physical Measures – Peak Force

Since a 2^4 randomized full factorial design was used in the experiment, peak – instantaneous initial force measurements were analyzed using a generalized linear model with backwards elimination procedure. Statistical procedures were carried in Minitab Version17 for Microsoft Windows. Backwards elimination was used to remove the least significant variables for each step until all of the variables have a p-value less than the specified type I error [30].

Psychophysical Self Reported Exertion Data

A Pearson correlation test was run on the psychophysical perceived exertion data to determine the presence or absence of correlation between the perceived exertion data and the initial force. This correlation was validated by adding weight as an additional correlation variable. "The larger the absolute value of the correlation coefficient, the stronger the linear relationship between the variables [30]".

5.2 Participant Data/Information

The following chart provides anthropometric as well as the demographic information for the 8 participants including mean and standard deviation (Table 4).

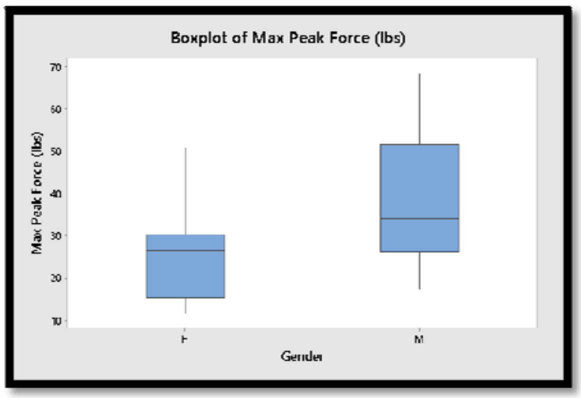
Table 4 - Participant Information & Statistics

Subject	Gender	Age	Weight	Standing Elbow Height
1	Male	29	195	47"
2	Male	26	185	44"
3	Male	49	215	44"
4	Male	45	183	43"
5	Female	57	125	42"
6	Female	43	200	42"
7	Female	48	189	41.5"
8	Female	38	190	42.5"
Range		26 - 57	125 - 215	
Male Mean (std. dev)		37.3 (9.9)	194.5 (12.7)	
Female Mean (std. dev)		46.5 (7.0)	176 (29.8)	
Overall Mean (std. dev)		41.9 (9.8)	185.3 (24.7)	

The boxplot summary (Figure 11) for maximum initial force by gender shows that males exerted more initial force when pushing the cart for both 250 lbs (113.4 kgs) and 750 lbs (340.4 kgs).

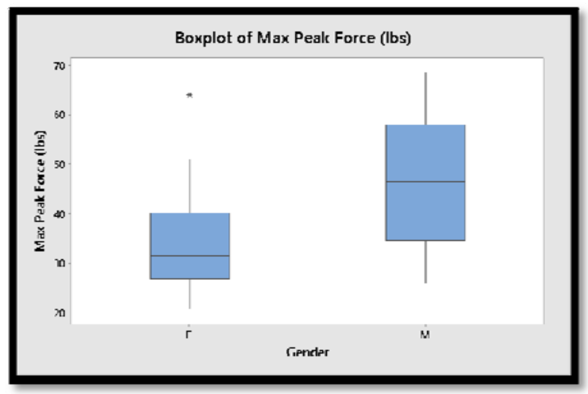
Figure 11 - Boxplot Gender Effect – Females versus Males

(Figure 11a)



250 lbs (113.4 kgs)

(Figure 11b)



750 lbs (340.4 kgs)

5.3 Physical Force Measurement Analysis –Initial Push Force

Using Minitab 17, a generalized linear model was fitted to the data following the backward elimination procedure, the results of which are summarized in Figure 12. In this model fixture, wheel type, wheel position, and weight were treated as the main factors while participants were treated as a blocking factor to accommodate the expected variability within subjects.

Figure 12 - General Linear Model

General Linear Model: Max Peak For versus Weight (lbs), Wheel Type, ...

Method

Factor coding (-1, 0, +1)

Backward Elimination of Terms

Candidate terms: Weight (lbs), Wheel Type, Fixture, Wheel Position, Participant

	-----Step 1----		-----Step 2----	
	Coef	P	Coef	P
Constant	31.316		31.317	
Weight (lbs)	-9.249	0.000	-9.250	0.000
Wheel Type	-1.148	0.068	-1.148	0.067
Fixture	-0.223	0.721		
Wheel Position	-1.545	0.014	-1.545	0.014
Participant	12.30	0.000	12.31	0.000
S	7.03694		7.01067	
R-sq	76.96%		76.93%	
R-sq(adj)	74.77%		74.96%	
R-sq(pred)	71.95%		72.39%	
Mallows' Cp	12.00		10.13	

α to remove = 0.1

Given a 90% confidence level, it was found that only wheel type, wheel position, weight, and participant significantly affected the initial push force. In the following section we present and discuss the results of the analysis that were carried out to test each of the three hypotheses.

Test of hypothesis 1:

1. Split-wheel design will affect the initial applied peak force required to move a four wheeled cart.

Hypothesis 1 a: Split wheels will reduce the initial applied peak force when the rear wheels are positioned at 90 degrees to the direction of travel.

Hypothesis 1 b: Split wheels will affect the initial applied peak force when the rear wheels are positioned at 0 degrees (aligned with the direction of travel).

Figure 13 indicates that the interaction between wheel type and position has a p-value of 0.947, hence it is not significant. However, both factors are individually significant. In this analysis, weight was treated as a fixed factor, whose significance was expected. To account for the expected variability within participants, the participant variable was treated as a blocking factor, which also turned out to be significant.

Figure 13 - ANOVA: Max Peak Initial Force vs Wheel Type & Wheel Position

General Linear Model: Max Peak For versus Wheel Type, Wheel Positi, ...

Factor	Type	Levels	Values
Wheel Type	fixed	2	Single, Swivel Eaz (dual)
Wheel Position	fixed	2	F0, R0, F0, R90
Weight (lbs)	fixed	2	250, 750
Fixture	fixed	2	Off Set Pivot, Standard
Participant	random	8	1, 3, 4, 5, 6, 7, 8, 9

Analysis of Variance for Max Peak Force (lbs), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Wheel Type	1	131.2	168.5	168.5	3.37	0.069
Wheel Position	1	254.3	305.1	305.1	6.11	0.015
Wheel Type*Wheel Position	1	1.1	0.2	0.2	0.00	0.947
Weight (lbs)	1	10632.5	10939.7	10939.7	219.02	0.000
Fixture	1	16.4	6.3	6.3	0.13	0.722
Participant	7	8146.7	8146.7	1163.8	23.30	0.000
Error	115	5743.9	5743.9	49.9		
Total	127	24926.1				

S = 7.06734 R-Sq = 76.96% R-Sq(adj) = 74.55%

Figures 14 and 15 are the main effects and interaction plots for wheel type and wheel position, respectively.

Figure 14 - Main Effects Plots

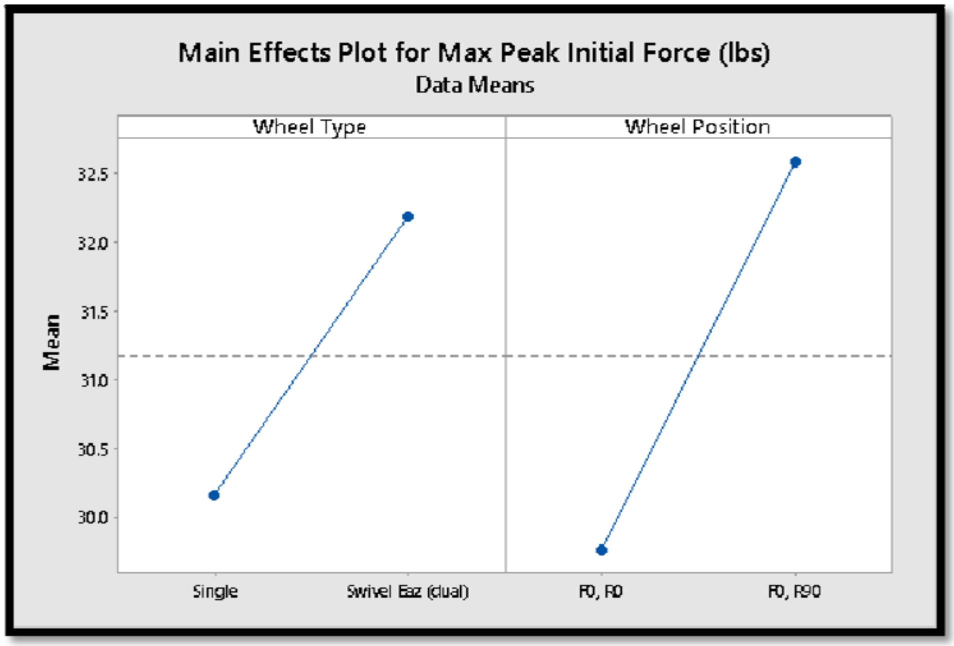
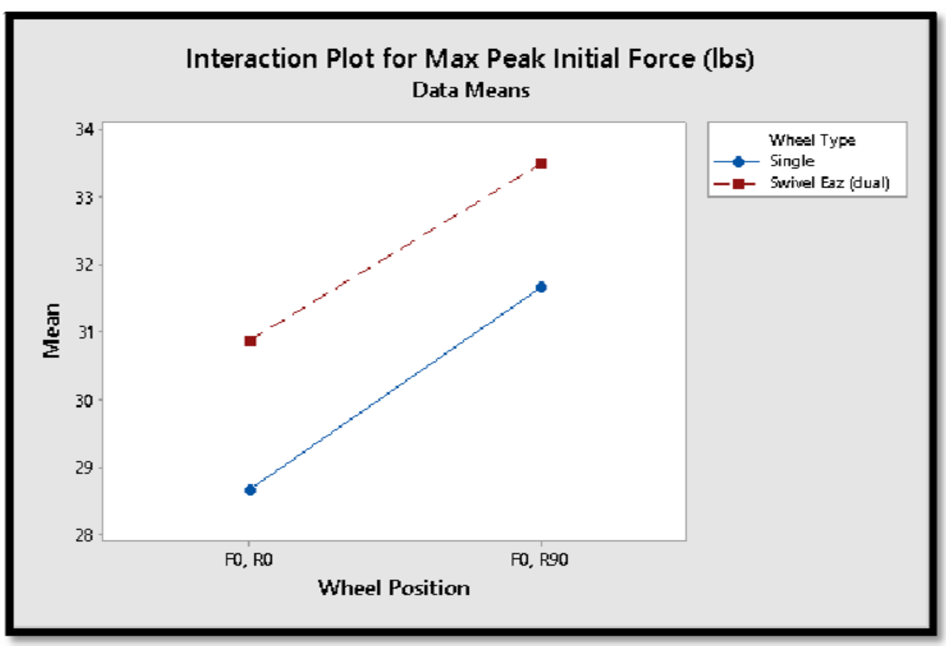


Figure 15 - Interaction Plot



Test of hypothesis 2:

The "offset pivot" caster mounting will affect the initial peak applied force required to move a four wheeled cart.

Hypothesis 2 a: The offset pivot caster mounting will reduce the initial applied peak force required to move the cart when the rear wheels are positioned at 90 degrees to the direction of travel.

Hypothesis 2 b: The offset pivot caster mounting affect the initial applied peak force when the rear wheels are positioned at 0 degrees (aligned with the direction of travel).

There is a statistically significant interaction between wheel type and caster type on the initial applied peak force required to move a four wheeled cart.

From the ANOVA in Figure 16, the interaction between the fixture and wheel position is significant, with a p-value of 0.046.

Figure 16 - ANOVA

General Linear Model: Max Peak For versus Weight (lbs), Wheel Type, ...

Factor	Type	Levels	Values
Weight (lbs)	fixed	2	250, 750
Wheel Type	fixed	2	Single, Swivel Eaz (dual)
Fixture	fixed	2	Off Set Pivot, Standard
Wheel Position	fixed	2	F0, R0, F0, R90
Participant	random	8	1, 3, 4, 5, 6, 7, 8, 9

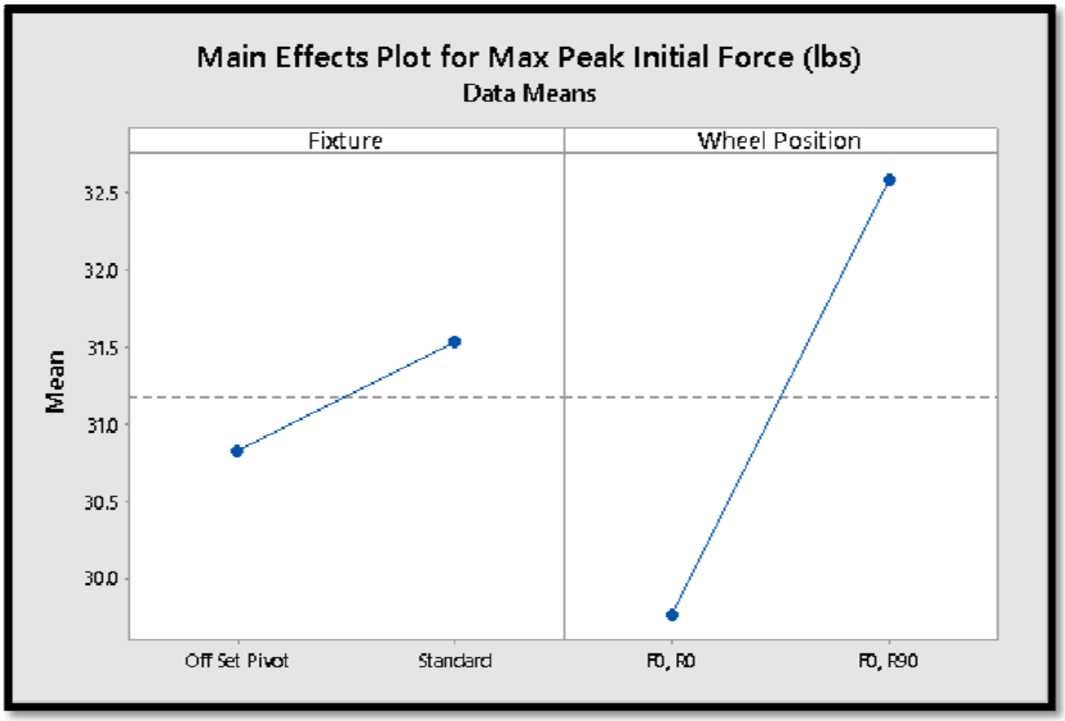
Analysis of Variance for Max Peak Force (lbs), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Weight (lbs)	1	10632.5	10936.7	10936.7	226.67	0.000
Wheel Type	1	131.2	168.1	168.1	3.48	0.065
Fixture	1	16.4	6.4	6.4	0.13	0.716
Wheel Position	1	254.3	304.6	304.6	6.31	0.013
Fixture*Wheel Position	1	240.4	195.4	195.4	4.05	0.046
Participant	7	8102.7	8102.7	1157.5	23.99	0.000
Error	115	5548.7	5548.7	48.2		
Total	127	24926.1				

S = 6.94620   R-Sq = 77.74%   R-Sq(adj) = 75.42%

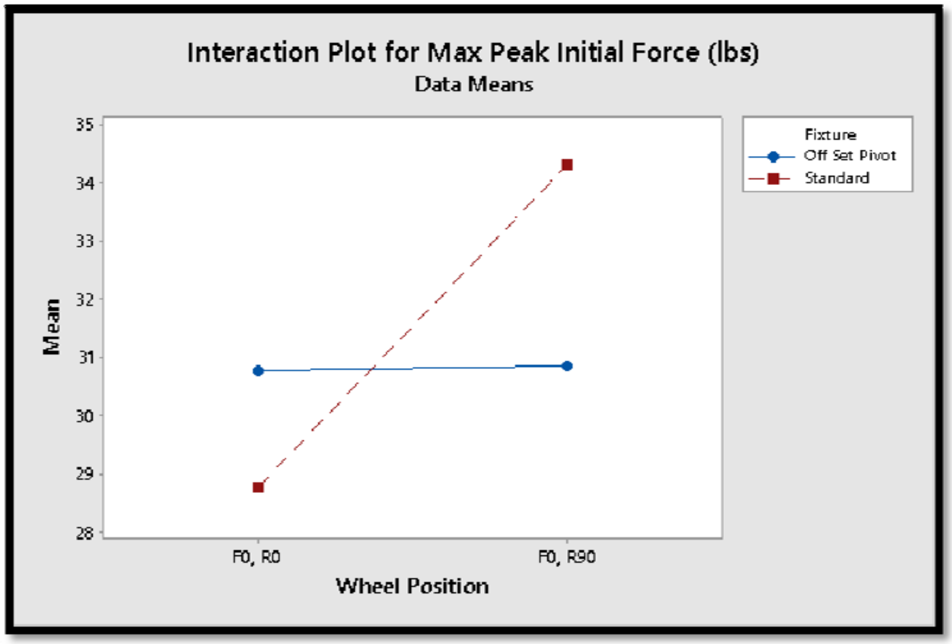
Even though fixture as a single main factor was not significant, the offset pivot fixture registered lower initial forces thus providing validation for considering investing in the offset pivot fixture in place of the standard design fixture (Figure 17).

Figure 17 - Main Effects Plot



In Figure 18, the Interaction Plot for fixture and wheel position, it can be seen that the offset pivot caster remains relatively consistent in performance across the two positions. This validates the need to invest in the offset caster type. In addition, with the rear wheels perpendicular to the direction of travel the standard fixture registered remarkably high initial applied force.

Figure 18 - Interaction Plot



Test for hypothesis 3:

Quantify the significance of the three main factors (wheel type, caster type and wheel position) on the peak force required to move a four wheeled cart.

Hypothesis 3 a: The three main factors will have a significant interactive effect on the peak force.

Hypothesis 3 b: The three main factors will not have a significant interactive effect on the peak force.

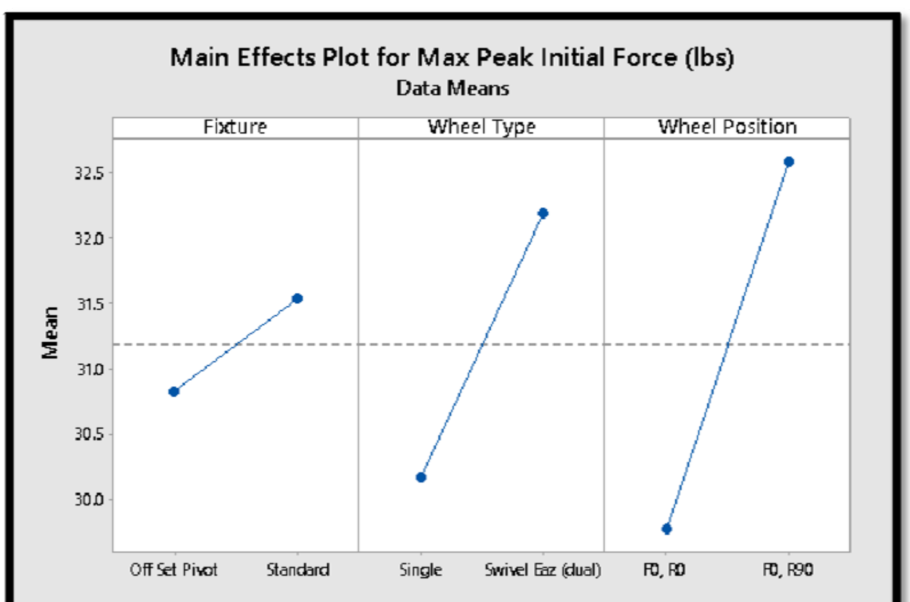
Figure 19 gives a summary of the 3rd and 4th steps in the linear model building procedure. It can be observed that the interaction between fixture and wheel type is not significant with a p-value of 0.142 which is near the threshold of 0.1. The interaction between fixture and wheel type (Figure 21), though significant is not dependent on wheel position.

Figure 19 - ANOVA, Fixture - Wheel Type

	-----Step 3----		-----Step 4----	
	Coef	P	Coef	P
Constant	31.319		31.318	
Blocks	12.44	0.000	12.39	0.000
Fixture	-0.220	0.709	-0.221	0.709
Wheel Type	-1.150	0.053	-1.149	0.054
Weight (lbs)	-9.251	0.000	-9.251	0.000
Wheel Position	-1.547	0.010	-1.546	0.010
Fixture*Wheel Type	-0.873	0.141	-0.873	0.142
Fixture*Weight (lbs)				
Fixture*Wheel Position	1.233	0.039	1.234	0.039
Wheel Type*Weight (lbs)	1.808	0.003	1.807	0.003
Wheel Type*Wheel Position				
Weight (lbs)*Wheel Position	0.723	0.222		

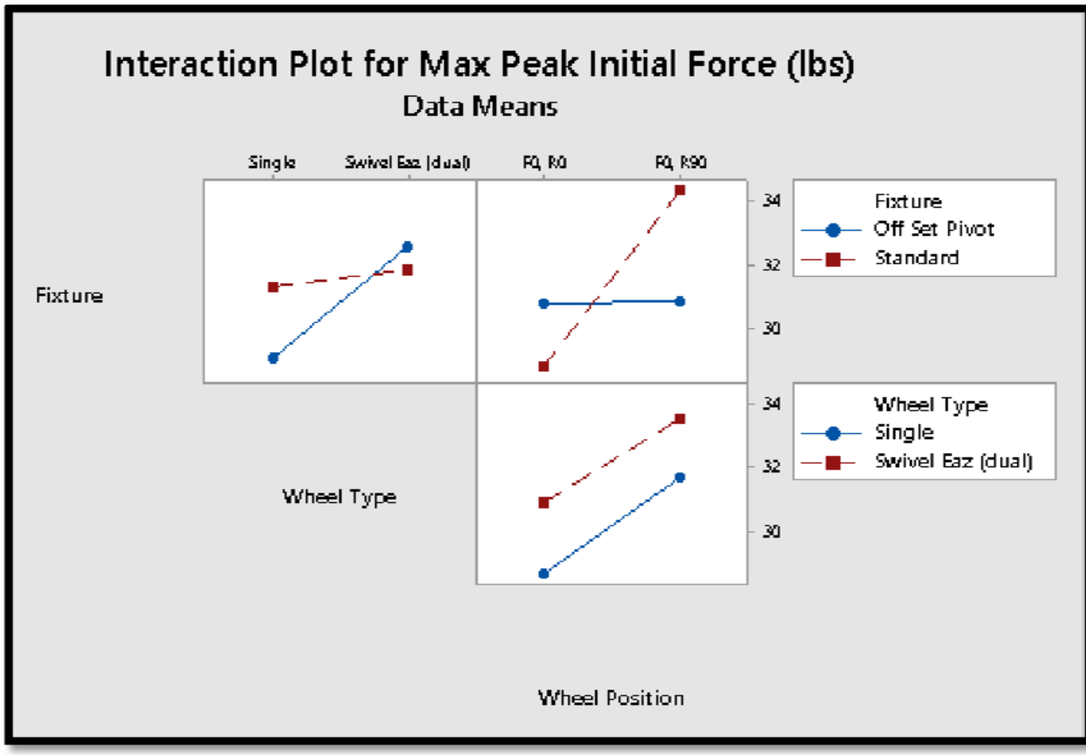
When using the offset fixture it seems advisable to use the single wheel; however when the dual wheel type is used there does not seem to be a difference whether the standard or offset pivot is used (Figure 21). It is advisable to invest in the offset pivot fixture; however as far as the type of wheel it seems the single wheel performs better. Though not considered in this study, there may be other sets of factors that would qualify the need to invest in the Swivel Eaz™ (dual wheel).

Figure 20 - Main Effects Plot, Fixture - Wheel Type - Wheel Position



In addition, the interaction plot between fixture and wheel type in Figure 21 shows that the initial peak force is reduced most when the single wheel type is incorporated into the offset pivot (Swivel Eaz™ Pro) fixture which kept initial force nearly consistent between the two wheel positions.

Figure 21 - Interaction Plot; Fixture - Wheel Type - Wheel Position



5.4 Psychophysical Analysis of Perceived Exertion

To test the strength of the relationships between weight, force, and perceived exertion on the shoulders and back, a Pearson's Correlation test was used. It is evident from Figure 22 that a strong positive correlation exists between these four variables. Weight was added as a correlation factor to validate the positive correlation between the self reported perceived exertion responses. A strong relationship exists between weight and perceived exertion at the shoulder and back with a Pearson correlation of 0.609 and 0.597, respectively (Figure 22).

Figure 22 - Pearson's Correlation, Back – Shoulder - Weight

Correlation: Weight (lbs), Max Peak For, shoulder_rat, back_rating_, Preference

	Weight (lbs)	Max Peak Force (	shoulder_rating_
Max Peak Force (	0.653		
	0.000		
shoulder_rating_	0.609	0.431	
	0.000	0.000	
back_rating__tra	0.597	0.378	0.930
	0.000	0.000	0.000
Preference	0.234	0.298	0.295
	0.008	0.001	0.001

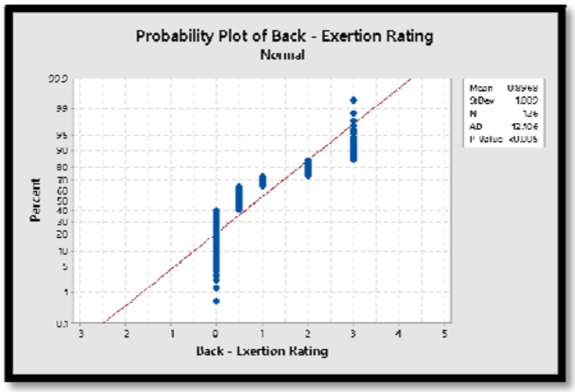
	back_rating__tra
Preference	0.247
	0.005

Cell Contents: Pearson correlation
P-Value

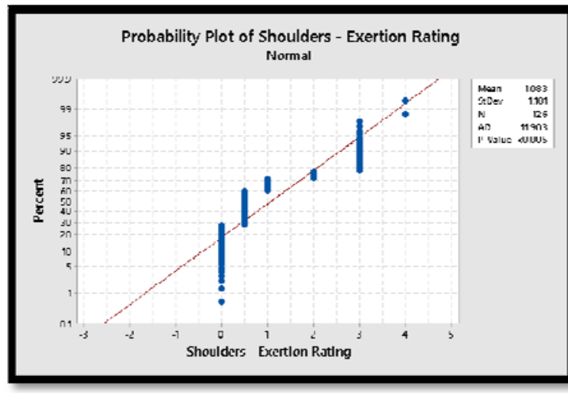
The Anderson-Darling Normality test was conducted to determine if the perceived exertion data were normally distributed. Evident in Figures 23 a-b, both perceived exertion data are not normally distributed.

Figure 23 - Normal Probability, Shoulder and Back

(Figure 23a)



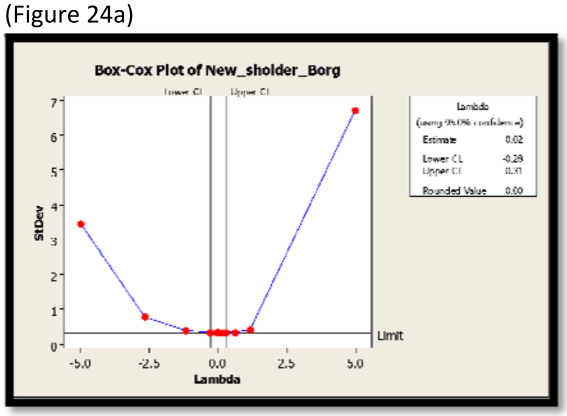
(Figure 23b)



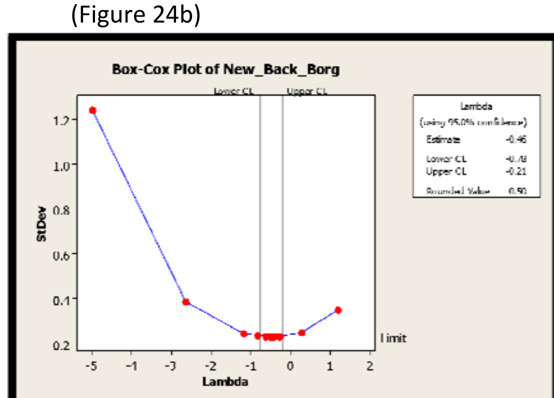
It was therefore necessary to transform the data using the Box Cox power transformation model as seen Figures 24 a-b.

Figure 24 - Box Cox - Shoulder and Back Data Transformation

(Figure 24a)



(Figure 24b)



For consistency of interpretation, shoulders and back Borg ratings of perceived exertion were given a logarithmic transformation. General linear models using the backward elimination procedure were constructed for both of the dependent variables. Weight was added as a correlation factor to validate the positive correlation between the self reported perceived exertion responses. Wheel position was a significant factor in the analysis of perceived physical exertion for the shoulder ($p = 0.02$) (Figure 25).

Figure 25 - ANOVA General Linear Model - Shoulders

Backward Elimination of Terms

Candidate terms: Blocks, Fixture, Wheel Type, Weight (lbs), Wheel Position, Fixture*Wheel Type, Fixture*Weight (lbs), Fixture*Wheel Position, Wheel Type*Weight (lbs), Wheel Type*Wheel Position, Weight (lbs)*Wheel Position

	------Step 1-----		------Step 2-----	
	Coef	P	Coef	P
Constant	0.1946		0.1946	
Blocks	-0.8011	0.000	-0.8011	0.000
Fixture	0.0313	0.355	0.0313	0.353
Wheel Type	-0.0494	0.145	-0.0494	0.143
Weight (lbs)	-0.4375	0.000	-0.4375	0.000
Wheel Position	-0.0802	0.019	-0.0803	0.018
Fixture*Wheel Type	0.0153	0.651	0.0153	0.649
Fixture*Weight (lbs)	-0.0663	0.051	-0.0663	0.050
Fixture*Wheel Position	0.0287	0.396	0.0287	0.392
Wheel Type*Weight (lbs)	-0.0252	0.455	-0.0253	0.453
Wheel Type*Wheel Position	-0.0303	0.370	-0.0302	0.369
Weight (lbs)*Wheel Position	0.0047	0.888		
S	0.376918		0.375219	
R-sq	76.92%		76.91%	
R-sq(adj)	73.28%		73.52%	
R-sq(pred)	68.61%		69.17%	
Mallows' Cp	18.00		16.02	

	------Step 3-----		------Step 4-----	
	Coef	P	Coef	P
Constant	0.1943		0.1939	
Blocks	-0.8008	0.000	-0.8004	0.000
Fixture	0.0317	0.346	0.0322	0.336
Wheel Type	-0.0491	0.144	-0.0486	0.147
Weight (lbs)	-0.4379	0.000	-0.4384	0.000
Wheel Position	-0.0803	0.018	-0.0804	0.017
Fixture*Wheel Type				
Fixture*Weight (lbs)	-0.0660	0.050	-0.0655	0.051
Fixture*Wheel Position	0.0287	0.391	0.0287	0.391
Wheel Type*Weight (lbs)	-0.0249	0.458		
Wheel Type*Wheel Position	-0.0302	0.367	-0.0301	0.367
Weight (lbs)*Wheel Position				
S	0.373867		0.373117	
R-sq	76.87%		76.75%	
R-sq(adj)	73.71%		73.82%	
R-sq(pred)	69.64%		70.05%	
Mallows' Cp	14.23		12.77	

	------Step 5-----		------Step 6-----	
	Coef	P	Coef	P
Constant	0.1939		0.1939	
Blocks	-0.8004	0.000	-0.8004	0.000
Fixture	0.0323	0.335	0.0323	0.333
Wheel Type	-0.0486	0.146	-0.0486	0.146
Weight (lbs)	-0.4385	0.000	-0.4386	0.000
Wheel Position	-0.0799	0.018	-0.0804	0.017
Fixture*Wheel Type				
Fixture*Weight (lbs)	-0.0655	0.051	-0.0655	0.051
Fixture*Wheel Position				
Wheel Type*Weight (lbs)				
Wheel Type*Wheel Position	-0.0305	0.360		
Weight (lbs)*Wheel Position				

	Step 5	Step 6
S	0.372687	0.372431
R-sq	76.60%	76.42%
R-sq(adj)	73.88%	73.91%
R-sq(pred)	70.38%	70.68%
Mallows' Cp	11.50	10.33

	------Step 7-----	
	Coef	P
Constant	0.1930	
Blocks	-0.7995	0.000
Fixture	0.0332	0.323
Wheel Type		
Weight (lbs)	-0.4394	0.000
Wheel Position	**-0.0804**	**0.017**
Fixture*Wheel Type		
Fixture*Weight (lbs)	-0.0647	0.055
Fixture*Wheel Position		
Wheel Type*Weight (lbs)		
Wheel Type*Wheel Position		
Weight (lbs)*Wheel Position		

	Step 7
S	0.374295
R-sq	75.97%
R-sq(adj)	73.65%
R-sq(pred)	70.64%
Mallows' Cp	10.42

α to remove = 0.1

Fixture was a significant factor in the analysis of perceived physical exertion for the Back (p= 0.04) (Figure 26).

Figure 26 - ANOVA General Linear Model – Back

Backward Elimination of Terms

Candidate terms: Blocks, Fixture, Wheel Type, Weight (lbs), Wheel Position, Fixture*Wheel Type, Fixture*Weight (lbs), Fixture*Wheel Position, Wheel Type*Weight (lbs), Wheel Type*Wheel Position, Weight (lbs)*Wheel Position

	------Step 1-----		------Step 2-----	
	Coef	P	Coef	P
Constant	0.0542		0.0542	
Blocks	-0.6607	0.000	-0.6607	0.000
Fixture	0.0690	0.052	0.0690	0.051
Wheel Type	-0.0451	0.200	-0.0451	0.198
Weight (lbs)	-0.4366	0.000	-0.4366	0.000
Wheel Position	-0.0274	0.436	-0.0275	0.431
Fixture*Wheel Type	0.0208	0.555	0.0208	0.553
Fixture*Weight (lbs)	-0.0855	0.016	-0.0855	0.016
Fixture*Wheel Position	0.0142	0.686	0.0143	0.682
Wheel Type*Weight (lbs)	-0.0236	0.502	-0.0236	0.500
Wheel Type*Wheel Position	-0.0086	0.806		
Weight (lbs)*Wheel Position	0.0095	0.787	0.0093	0.789
S	0.392417		0.390723	
R-sq	75.68%		75.66%	
R-sq(adj)	71.85%		72.09%	
R-sq(pred)	66.90%		67.49%	
Mallows' Cp	18.00		16.06	

	------Step 3-----		------Step 4-----	
	Coef	P	Coef	P
Constant	0.0542		0.0542	
Blocks	-0.6607	0.000	-0.6607	0.000
Fixture	0.0690	0.050	0.0691	0.049
Wheel Type	-0.0451	0.196	-0.0451	0.195
Weight (lbs)	-0.4366	0.000	-0.4367	0.000
Wheel Position	-0.0276	0.427	-0.0274	0.429
Fixture*Wheel Type	0.0208	0.551	0.0208	0.550
Fixture*Weight (lbs)	-0.0855	0.015	-0.0855	0.015
Fixture*Wheel Position	0.0145	0.677		

Wheel Type*Weight (lbs)	-0.0236	0.498	-0.0236	0.497
Wheel Type*Wheel Position				
Weight (lbs)*Wheel Position				
S	0.389071		0.387620	
R-sq	75.65%		75.61%	
R-sq(adj)	72.33%		72.53%	
R-sq(pred)	68.04%		68.58%	
Mallows’ Cp	14.13		12.30	

	------Step 5-----		------Step 6-----	
	Coef	P	Coef	P
Constant	0.0538		0.0534	
Blocks	-0.6603	0.000	-0.6599	0.000
Fixture	0.0695	0.047	0.0700	0.044
Wheel Type	-0.0447	0.197	-0.0443	0.200
Weight (lbs)	-0.4371	0.000	-0.4376	0.000
Wheel Position	-0.0275	0.427	-0.0275	0.425
Fixture*Wheel Type				
Fixture*Weight (lbs)	-0.0851	0.015	-0.0847	0.015
Fixture*Wheel Position				
Wheel Type*Weight (lbs)	-0.0231	0.505		
Wheel Type*Wheel Position				
Weight (lbs)*Wheel Position				
S	0.386509		0.385564	
R-sq	75.53%		75.43%	
R-sq(adj)	72.69%		72.82%	
R-sq(pred)	69.02%		69.44%	
Mallows’ Cp	10.65		9.09	

	------Step 7-----		------Step 8-----	
	Coef	P	Coef	P
Constant	0.0534		0.0526	
Blocks	-0.6599	0.000	-0.6591	0.000
Fixture	**0.0700**	**0.044**	**0.0708**	**0.042**
Wheel Type	-0.0443	0.199		
Weight (lbs)	-0.4376	0.000	-0.4384	0.000
Wheel Position				
Fixture*Wheel Type				
Fixture*Weight (lbs)	-0.0847	0.015	-0.0839	0.016
Fixture*Wheel Position				
Wheel Type*Weight (lbs)				
Wheel Type*Wheel Position				
Weight (lbs)*Wheel Position				
S	0.384958		0.386073	

R-sq	75.29%	74.93%
R-sq(adj)	72.91%	72.75%
R-sq(pred)	69.81%	69.89%
Mallows' Cp	7.71	7.31
α to remove = 0.1		

It is unclear why the wheel design seems to significantly affect the self reported shoulder exertion rating. Similarly, it is also not clear why the caster design seems to significantly affect the self reported back exertion rating. We therefore propose for further studies, especially the physiological impact of the wheel and caster designs on the push and pull actions.

The perceived exertion rating mean for the shoulders while pushing the cart with a gross weight of 750 lbs (340.2 kgs), using offset pivot fixture, Swivel Eaz (dual) wheels, and wheels positioned perpendicular to the direction of travel was 2.0 with a standard deviation (s.d) of 1.16. The perceived exertion on the shoulders, using a Borg CR10 scale, was rated as Light. Perceived exertion on the back, using the same combination, was rated with a mean of 1.68 and s.d. of 1.19. A 1.68 rating falls between Very Light and Light on the scale.

The perceived exertion rating mean for the shoulders while pushing the cart with a gross weight of 750 lbs (340.2 kgs), using a standard fixture, Swivel Eaz (dual) wheels, and wheels positioned perpendicular to the direction of travel was 1.87 (Very Light – Light) with a s.d. of 1.33. Perceived exertion on the back, using the same combination, had a rating mean of 1.62 (Very Light – Light) and s.d. of 1.41. All of the combinations and their perceived exertions can be found in Appendix C.

The standard fixture with a single wheel positioned perpendicular to the direction of travel with 750 lbs (340.2 kgs) was actually rated lowest when compared to the other two wheel - fixture combinations. This is attributed to the statistically significant interaction between the wheel type and the caster design, where the least initial push force was required when using a cart with the single wheel and offset pivot caster combination. This claim is supported by the data summary in Figures 27 and 28.

Chapter 6: Discussion

The purpose of this research was to investigate the effects of wheel and fixture designs on pushing force of a four-wheeled cart. The following discussion is a review of the hypothesis and the practical effectiveness and application.

6.1 Hypothesis Discussion

Split-wheel design will effect the initial applied peak force required to move a four wheeled cart.

When the wheels were positioned perpendicular with direction of travel (F0R90) and the Swivel Eaz ™ dual wheel was used in the standard fixture, the peak applied force mean was 34.6 lbs and was 1.4 % greater than the peak applied force mean of 34.1 lbs attained when the single wheel was used in the same standard fixture. Taking into account possible statistical error, the difference of 1.4% may not be significant enough to differentiate one wheel as a better option over the other (Figures 27 – 28).

Figure 27 - Boxplot - Peak Initial Force

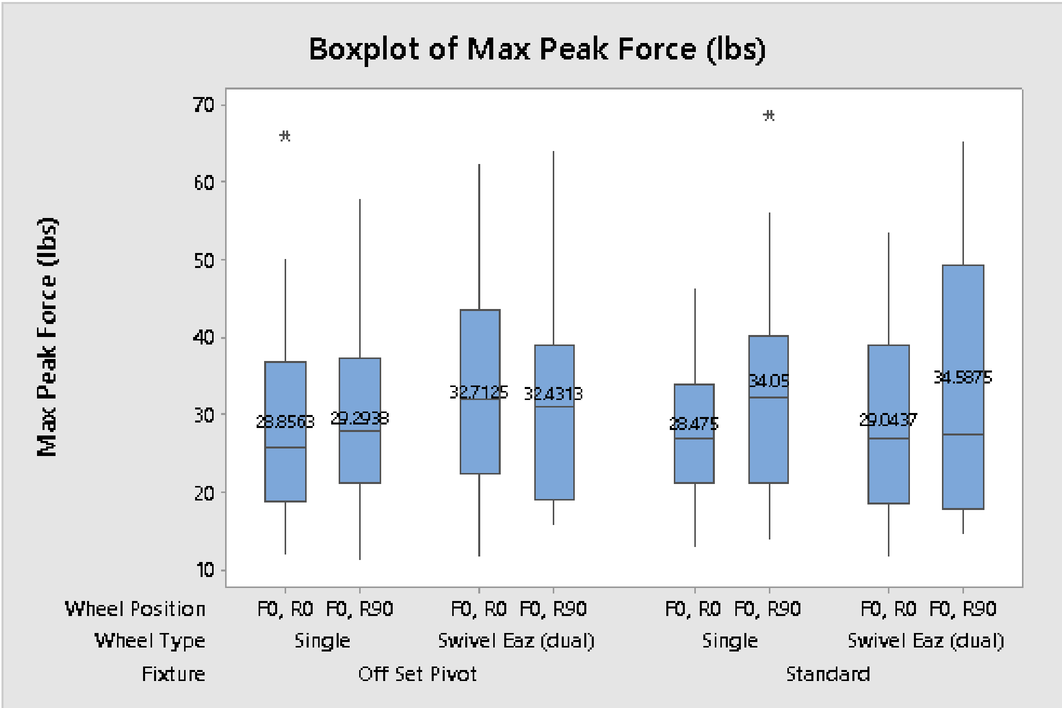


Figure 28 - Summary of Box Plot of Combinations

Wheel Position	Fixture Type	Wheel Type	Mean Peak Force	Difference (lbs)	% Difference
90 deg	Standard	Swivel Eaz (dual)	34.6	.5	1.4
90 deg	Standard	Single	34.1		
90 deg	Offset Pivot	Swivel Eaz (dual)	32.4	3.1	9.6
90 deg	Offset Pivot	Single	29.3		
0 deg	Standard	Swivel Eaz (dual)	29.0	.5	1.7
0 deg	Standard	Single	28.5		
0 deg	Offset Pivot	Swivel Eaz (dual)	32.7	3.9	11.9
0 deg	Offset Pivot	Single	28.8		

When the wheels were positioned in line to the direction of travel (F0R0) and the Swivel Eaz ™ dual wheel was used in the standard fixture, the peak applied force mean was 34.1 lbs (15.5 kgs) and was 1.7% greater than the peak applied force mean of 28.5 lbs(12.9 kgs) attained when the single wheel was used in the same standard fixture. Again, the difference between the two combinations may not be significant enough to differentiate one wheel over the other as a better option (Figures 27– 28).

The "offset pivot" caster mounting will effect the initial peak applied force required to move a four wheeled cart.

When the single wheels were positioned perpendicular to the direction of travel (F0R90) and used with the offset pivot (Swivel Eaz ™ Pro) fixture the applied peak force mean was 29.3 lbs (13.3 kgs). This was 16.4% lower than the applied peak force mean of 29.3 lbs (13.3 kgs) which was attained when a single wheel was used in a standard fixture and also positioned perpendicular to the direction of travel. In other words, when the rear wheels were positioned at 90 degrees to the direction of travel, offset pivot fixture (caster) had 16.4% lower applied peak force mean versus the single wheel in the standard fixture.

Quantify the significance of the three main factors (wheel type, caster type and wheel position) on the peak force required to move a four wheeled cart.

When using the offset fixture it seems advisable to use the single wheel; however when the dual wheel type is used there does not seem to be a difference whether standard or offset pivot is used. It seams advisable to invest in the offset pivot fixture; however as far as the type of wheel it seems the single wheel performs better in this particular application. Though not considered in this study, there may be other sets of factors that would qualify the need to invest in the Swivel Eaz™ (dual wheel). For example, this study did not consider wheel surface durability or wheel bearing wear over time.

6.2 Variability Between Subjects

There was variation in the peak force ranges between the 8 different subjects. For example, in combination 4 when the gross cart weight was 250 lbs (113.4 kgs), rear wheels were positioned at F0R90, Swivel Eaz (dual) wheels were mounted on the standard fixture, the minimum peak applied force was 14.3 lbs (6.5 kgs). The maximum peak force applied by a participant was 33.2 lbs (15.1 kgs) the difference in the range 18.9 lbs (8.6 kgs) and the standard deviation was 6.69 lbs (3.0 kgs) (Table 5). In combination 12, when the gross cart weight was 750 lbs (340.2 kgs), rear wheels were positioned at F0R90, Swivel Eaz (dual) wheels were mounted on the standard fixture, the minimum peak applied force was 27.2 lbs (12.3 kgs). The maximum peak force applied by a participant was 65.4 lbs (29.7 kgs) the difference in the range is 38.2 lbs (17.3 kgs) and the standard deviation was 15.41 (7.0 kgs). The overall range differences for each of the ranges in each combination varied from 16.5 – 45.5.

Table 5 - Applied Peak Force Range

		Range				
Combination	Weight (lbs)	Mean (lbs)	Min (lbs)	Max (lbs)	Diff	St. Dev
1	250	23.1	12.6	34.1	21.5	7.39
2	250	25.25	13.7	36.1	22.4	9.2
3	250	19.79	11.5	28	16.5	6.84
4	250	20.91	14.3	33.2	18.9	6.69
5	250	20.01	11.7	31.2	19.5	7.19
6	250	22.54	11.1	38.5	27.4	8.67
7	250	22.08	11.4	35.4	24	9.58
8	250	22.86	15.7	36.2	20.5	7.55
9	750	33.85	21	46.4	25.4	10.2
10	750	42.85	25.4	68.6	43.2	15.56
11	750	38.3	26.2	53.5	27.3	10.87
12	750	48.26	27.2	65.4	38.2	15.41
13	750	37.7	20.6	66.1	45.5	14.61
14	750	36.05	20.95	57.9	36.95	12.07
15	750	43.35	29.3	62.5	33.2	12.11
16	750	42	28.9	64.1	35.2	11.31

6.3 Perceived Exertion

As expected, there was a strong relationship between the amount of weight the participant had to push and their level of perceived exertion. What remains unclear is why wheel type was a significant factor in the level of perceived exertion for the shoulder and not with the back. In addition, it is unclear why the fixture is the significant factor in perceived level of exertion in the back. Participants did rate the level of perceived exertion slightly higher on both the shoulder and the back when pushing the 750 lb (340.2 kgs) cart with the offset pivot, Swivel Eaz wheel, and positioned perpendicular to the direction of travel versus the same combination and using the standard fixture, Light compared to Very Light-Light, respectively.

6.4 Application of the Results/Psychophysical Application

Many of the force differences observed in this study were modest, and given the large variability between subject variability, it could be argued that there are no practical differences between any of the wheel-fixture combinations. However, the offset pivot fixture could be a valuable intervention in some common situations. To illustrate this, consider the following scenario.

6.4.1 Scenario 1 – Changing Fixtures

A worker is required to push a cart for 200 feet (61 m) two times per hour with the handle height at hip level. The initial force required to get the cart into motion when the wheels are perpendicular to the direction of travel is 40 lbs (18.1 kgs). The sustained force required to keep the cart in motion is 19.0 lbs. According to the Snook and Cirello tables [9]-[32], the initial force of 40 lbs (18.1 kgs) is acceptable to 83% of males and 66% of females. The recommended design goal from Snook and Cirellio was for the task to be acceptable for at least 75% of females [9]-[32].

If a cart designer wanted to reduce the initial force when the wheels are positioned perpendicular to the direction of travel, they could install a set of offset pivot (Swivel Eaz ™ Pro) fixtures with single wheels. Based on results from this study, and if all other variables were equal, the applied peak force mean would be lowered by 16.1%. In other words, the peak force of 40 lbs (18.1 kgs) would be lowered to 33.6 lbs (15.2 kgs). This would now make the job acceptable to 84% of the females and 90% of the males [9]-[32]. It this case it seems advisable to implement the offset pivot fixture with the single wheel.

6.5 Limitations of the Study

6.5.1 Instantaneous Peak Force

Although, force data was recorded from when the cart started motion until after it stopped, this study only focused on the peak applied instantaneous force. There is a possibility that the tenth of a second data point was not representative of the actual average initial force. The median force over the brief initial period may be a better representation of initial force. Hence for future analysis in this study, average initial force in addition to the sustained push forces will be used as opposed to initial peak force.

6.5.2 Lateral Force

Lateral force was recorded during the study but it was not a focus for this thesis. It seems reasonable to expect that the offset pivot fixture would significantly reduce lateral movement when the cart is initially started, especially when the wheels are positioned at 90 degrees or otherwise out of alignment.

6.6 Contribution to the Body of Knowledge

The impact of this study is to introduce data and statistical analysis of a new style of wheel and fixture of which no published studies were found. The study demonstrated that if an organization is looking to reduce initial force when wheels are misaligned with the direction of travel the offset pivot (Swivel Eaz™ Pro) is a viable alternative.

6.7 Future Studies

Further study could be conducted on the Swivel Eaz ™ wheels to understand how they perform after being in-use for an extended period of time. The wheels and fixtures used were new at the start of the study. The wheels could also be tested over rough surfaces as it seems reasonable to expect the Swivel Eaz ™ dual wheels to perform better over surfaces that are not flat. As mentioned earlier, future study and analysis could look at the average initial force, the sustained force, and lateral force.

Chapter 7: Conclusion

The sponsor sought to investigate the effects of the wheel and fixture (caster) designs on pushing force of a four-wheeled cart. Based on the study findings and results from this analysis the following recommendations are being made to the sponsor:

1) If looking to reduce push force when the wheels are positioned perpendicular to the direction of travel, consider utilizing the Swivel Eaz™ Pro fixture with the single wheel; however, the cost of the Swivel Eaz™ Pro fixture may not be justifiable to only gain a 16% reduction in force.
2) Other factors should be considered when deciding whether to purchase the Swivel Eaz™ Pro fixture and Swivel Eaz™ dual wheels such as

longevity under rugged conditions and whether the wheels can traverse bumps or uneven surfaces more easily.

3) During the study, differences in the participant's perceived exertion ratings means seemed nearly inconsequential as the ratings for 750 lbs (340.2 kgs) ranged from 1.38 – 2.00 which falls between "Very Light – Light" for the shoulders and 1.19 – 1.81 "Very Light – Light" for the back. In other words, the differences in fixture and wheel type were effectively imperceptible to the participant.

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Appendices

Appendix A – Pre Screening Form

Pre – Screening Form

Date:_________________

Age:_____________________________ Gender: Male ☐ Female ☐

Height:__________ Weight:_______________

1) Are you currently experiencing any back or shoulder pain? YES NO

    a. If you answered YES to question 1 then you are not allowed to participate in the study.
    b. If you answered NO then continue to question 2…

2) Have you had any back or shoulder pain lasting more than 24 hours in the past 12 months ? YES NO

    a. If you answered YES to question 2, do you feel this pain will prohibit you from safely completing the task? YES NO

        i. If you answered YES to question 2a and feel the pain will prohibit you from safely completing the study then you are not allowed to participate in the study.

3) If you answered NO to question 2 then you are allowed to participate in the study. Thank you for assistance in this project.

4) If you are under the care of a physician and have restrictions regarding pushing, pulling, or other material handling tasks then you are not allowed to participate.

If you have any questions regarding this study, please contact the researcher David Wein at 920-216-3598 or dwein@oshkoshcorp.com.

Thank you.

Appendix B – Participant Information

Participant Information

Assigned Identification No:____________ Date:_________________________

Age: _______ Gender (circle one): Male Female

Height (feet & inches): _______________ Weight (lbs.): _________________

Standing Elbow Height (in.) ___________

Appendix C – Pain and Exertion Rating

Pain and Exertion Rating

Participant Identification Number: ______________ Date:_______________

Directions: Trials will be randomized by drawing 16 numbers and assigning them to the 16 trials as the experimental order for each participant.

Combo #	Cart	Weight (lbs)	Fixture	Wheel Type	Wheel Position
1	1	250	Standard	Single	F0, R0
2	1	250	Standard	Single	F0, R90
3	1	250	Standard	Swivel Eaz (dual)	F0, R0
4	1	250	Standard	Swivel Eaz (dual)	F0, R90
5	2	250	Off Set Pivot	Single	F0, R0
6	2	250	Off Set Pivot	Single	F0, R90
7	2	250	Off Set Pivot	Swivel Eaz (dual)	F0, R0
8	2	250	Off Set Pivot	Swivel Eaz (dual)	F0, R90
9	1	750	Standard	Single	F0, R0
10	1	750	Standard	Single	F0, R90
11	1	750	Standard	Swivel Eaz (dual)	F0, R0
12	1	750	Standard	Swivel Eaz (dual)	F0, R90
13	2	750	Off Set Pivot	Single	F0, R0
14	2	750	Off Set Pivot	Single	F0, R90
15	2	750	Off Set Pivot	Swivel Eaz (dual)	F0, R0
16	2	750	Off Set Pivot	Swivel Eaz (dual)	F0, R90

Please rate your exertion level by circling the number that corresponds to how hard this pushing task was on your shoulders and back.

Shoulders (circle your response)

0 No effort
0.5 Very, very light
1 Very light
2 Light
3 Moderate
4 Somewhat hard
5 Hard
6 More than hard
7 Very hard
8 More than very hard
9 Very, very hard
10 Unable to push

Back (circle your response)

0 No effort
0.5 Very, very light
1 Very light
2 Light
3 Moderate
4 Somewhat hard
5 Hard
6 More than hard
7 Very hard
8 More than very hard
9 Very, very hard
10 Unable to push

How well do you like the wheel fixture combination?

1 Strongly like
2 Like
3 Neither like nor dislike
4 Dislike
5 Strongly dislike